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29 August 2023

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Consultation Paper – 30 July 2022 and 7 October 2022 under-frequency events

We appreciate the opportunity to respond to the Authority's consultation paper *Draft Determination of Causer for the under-frequency events (UFE) that occurred on 30 July 2022 and 7 October 2022*, published 1 August 2023.

We agree with the Authority's draft determination of the causer of the UFE on 7 October 2022 and the MW lost from the event. We have answered the specific consultation questions in the appendix.

There have been subsequent internal and external investigations into the event. An independent review was conducted by PBA Consulting and suggested some opportunities for improvement which are listed below. Three of the five items were progressed by Transpower. The grid owner has completed items 1 and 2 in Q1 of 2023. Item 4 is being addressed as part of a Major Capex Proposal submitted to the Commerce Commission. Item 2 will not be implemented, and item 5 is noted, but unlikely to proceed in the short term.

The investigation report is attached, uploaded, and can be accessed in our website in this page (Transpower resolves grid emergency situation | Transpower).

Opportunity for improvement		Status	Comment
1)	Replace components in Pole 2 filter breaker outdoor junction box (ODJB)	Completed	In March 2023, all relevant legacy components have been replaced with modern equivalents on the F3 and F4 filter banks at Haywards and Benmore.
2)	Modify HVDC controls to respond to a filter fail-to-close by setting the filter to manual	Closed	Transpower has developed a software modification to automatically select a filter to Manual (unavailable for automatic switching by the Reactive Power Control or RPC) if it fails to close. This software modification has been tested in the GHOST simulator and also sent to Siemens (the HVDC control system original equipment manufacturer) for review. After discussions with Siemens this recommendation was decided to not be implemented due to potential impacts on other parts of the control system logic. The other fixes which have been implemented make this an acceptable outcome. As an additional safeguard the grid owner has modified its control room procedures to ensure that filter banks are manually made 'not available to RPC' after filter bank tripping.

3)	Fix bug in the software for the 'Pole Block for Multiple AC Filters Outages Logic'	Completed	Investigation of the software logic has uncovered a bug where the 'Pole Block for Multiple AC Filter Outages' logic fails to keep the slave pole blocked if it has recently been deblocked (less than 10 seconds) due to the persistence of a long deblock signal. An HVDC control system software modification was developed and tested by Transpower to fix the bug which caused the power reduction event. The modification was also reviewed and approved by Siemens. The modification was implemented onto the live system in February 2023 and tested on site to confirm that the bug had been fixed, all of which was successful.
4)	Improve HVDC resiliency by adding a 4th 'B' filter	In progress	The additional 'B' filter was proposed as Stage 3 of the HVDC Pole 3 Inter-Island Link project, however only Stage 1 and 2 were ultimately approved and delivered. Transpower has submitted a Major Capex Proposal to the Commerce Commission as part of the Net Zero Grid Pathways project (NZGP) on 5 December 2022. The proposal includes adding a 4th 'B' Filter at Haywards, among other upgrades to support the HVDC's operation by improving the average availability from 1071 MW to close to 1200 MW.
5)	Consider Voltage Source Converter (VSC) technology for future converters	Closed	Transpower has engaged in industry consultation regarding the future of Pole 2. Based on this Transpower has initiated a Pole 2 extension of life project as a least lifecycle cost solution to extend the life of Pole 2 out to 2040. When Pole 2 is finally retired, any decision to replace Pole 2 would likely be based on a modern VSC solution. This addresses many of the issues related to harmonics and reactive power requirements presented by the current Line Commutated Converters (LCC) converter technology.

Yours sincerely

Mark Ryall
GM Grid Delivery

Appendix: Response to questions

Questions	Comment
Q1. Do you agree with the draft determination that Genesis Energy Limited is the causer of the under-frequency event on 30 July 2022 at 6.13am? If not, please advise your view on the causer and give reasons.	No comment from the grid owner.
Q.2 Do you agree with the draft determination that Transpower New Zealand Limited, as the grid owner, is the causer of the under-frequency event on 7 October 2022 at 5:36am? If not, please advise your view on the causer and give reasons	We agree, the grid owner is the causer of the under-frequency event on 7 October 2022 at 5:36am.
Q3. Do you agree with the system operator's assessment that 144.50 MW was lost from the power system in the 30 July 2022 UFE? If not, please advise your view on the MW lost and give reasons.	No comment from the grid owner.
Q4. Do you agree with the system operator's assessment that 256.1 MW was lost from the power system in the 7 October 2022 UFE? If not, please advise your view on the MW lost and give reasons.	We agree with the calculated MW lost of 256.1MW.

Independent Review
HVDC Power Reduction Event
7 October 2022

Issued To:	Transpower New Zealand Ltd
Written By:	Ranil de Silva – Technical Director, PBA Consulting
Approved By:	Tony Armstrong – Director, PBA Consulting
Report Number:	JC-001-105 Final Report 16 November 2022

Revision Number	Description	Date	Author
0	Final Report	16/11/2022	J R de Silva

Disclaimer

The Reviewer's own opinions are presented in this report. These opinions are independent of Transpower, and are not necessarily the opinions of PBA Consulting or Unison Networks.

Acknowledgements

The reviewer thanks the staff at Transpower's HVDC & Power Electronics Group and the System Operator for their helpful discussion, and provision of background information, SER records, and TFR records.

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Executive Summary

On Wednesday 5 October 2022, the System Operator provided an industry briefing on the tight generation situation to meet a forecast high demand associated with an unseasonable cold snap for the next 2 days, Thursday and Friday 6-7 October 2022. The industry responded by cancelling a number of planned generation and transmission outages so as to improve the resilience of the system for the 2 days of concern.

Transpower's scheduled live line work on HVDC Pole 2 that required restarts to be turned off was cancelled to improve resilience. Haywards HVDC Filters F3A and F3B were on a 2-week scheduled outage and were not recalled as the filter outage was expected to have no impact on the HVDC transfer rating.

On the morning of Friday 7 October, the HVDC Link was running in Roundpower Mode with Pole 3 in monopole operation, transferring about 300 MW North. At 04:28 the HVDC controls attempted to connect Haywards Filter F4B, however the circuit breaker failed to close on red phase and tripped. There was no immediate effect on HVDC transfer, however if Haywards Filter F5B also tripped then HVDC transfer would be limited to about 70 MW as a monopole. Consequently, the System Operator issued a Customer Advice Notice and Warning Notice advising of the effect of the unplanned outage on Filter F4B and a risk of insufficient generation and reserve offers to meet demand and provide N-1 security for a contingent event for the morning peak.

Filter F4B was visually checked and the last alarm reset at 05:36 with Pole 3 in monopole operation at 410 MW North. As designed, the HVDC controls immediately transitioned to bipole operation and attempted to connect Filter F4B. Again, the circuit breaker failed to close on red phase and the filter tripped. The 'Pole Block for Multiple AC Filter Outages Logic' then blocked Pole 2 and HVDC transfer was maintained at 410 MW by Pole 3 in monopole operation.

At this point, Pole 2 unexpectedly deblocked and the HVDC resumed bipole operation. As the previous bipole to monopole transition had failed, the HVDC remained in bipole operation, however without Filters F3A, F3B, and F4B, the HVDC power transfer rapidly reduced by 270 MW from 410 MW to a power limit of 140 MW. The power reduction resulted in an under-frequency event in the North Island which tripped North Island interruptible load.

About 10 minutes later, the 'Pole Block for Multiple AC Filter Outages Logic' automatically blocked Pole 2. This allowed Pole 3 to operate as a monopole rated up to 840 MW continuous, however a Pole 3 trip could not be immediately compensated by Pole 2. Consequently HVDC power transfer was limited by the availability of North Island reserves to compensate for a Pole 3 trip.

As the morning peak demand approached, the already tight generation situation together with the restriction of the HVDC to Pole 3 monopole operation resulted in the System Operator issuing a Grid Emergency Notice at 07:15 for the North Island advising there was insufficient generation and reserve offers to meet North Island demand and provide N-1 security for a contingent event over the morning peak. North Island distributors responded by shedding controllable load. This restored N-1 security and there was no requirement to disconnect customers.

Filter F4B was successfully connected under manual control and remained in that state to prevent further automatic switching. This allowed normal bipole operation to resume and allowed the System Operator to end the Grid Emergency at 08:00 .

The root causes of the HVDC Power Reduction Event were :

1) The Haywards Filter F4B circuit breaker failed to close on red phase, tripping the filter and limiting HVDC transfer capacity. Similar intermittent faults over preceding years had previously been observed on Haywards Filter F3A but extensive investigations by Transpower and external contractors had not pinpointed the cause of the fault. Further investigations subsequent to the 7 October event suggest that 125 V close command signals are intermittently failing to pass through switches or contactors in the Outdoor Junction Box (ODJB) that interfaces the breaker to the HVDC control systems. These components have not been replaced since their original installation during the first HVDC upgrade in 1992.

2) A ‘Bug’ in the software logic for ‘Pole Block for Multiple AC Filter Outages’ which was implemented in 2017, after the 2013 HVDC upgrade. It appears that the 10 second signal used to deblock a pole is not well coordinated with the block signal from the ‘Pole Block for Multiple AC Filter Outages’ logic. In this event, the persistent deblock signal reversed the transition from bipole operation to monopole operation, leaving the HVDC running in bipole operation with transfer capacity significantly limited by the filter outages.

This review has identified a number of opportunities for Transpower to improve the reliability of the HVDC Link :

1) The HVDC & Power Electronics Team is currently considering replacing the components in all Pole 2 filter ODJB’s at both Haywards and Benmore. The Reviewer supports this approach, noting that replacing breaker ODJB components will require re-testing the signal paths through the ODJB, but will not require software modifications to the HVDC controls.

2) If a filter circuit breaker fails to close, the present HVDC controls are designed to leave the filter available for Reactive Power Control (RPC). Resetting protection alarms may result in the RPC immediately (and unexpectedly) connecting the filter if it is still required. It may be preferable to modify the HVDC controls to respond to a filter fail-to-close by setting the filter to manual (not available to the RPC). The HVDC Grid Asset Controller would then make the decision to make the filter available to RPC at a convenient time.

3) Fix the bug in the software logic for ‘Pole Block for Multiple AC Filter Outages’ that appears to be poorly coordinated with the 10-second long Pole deblock signal. Fixing this bug is likely to require a significant amount of time, effort, and re-testing on Transpower’s HVDC Simulator.

4) Transpower is presently considering adding a fourth 'B' filter at Haywards as well as a second STATCOM to provide additional redundancy to make the HVDC more resilient to outages. This will also increase the Northward rating from 1200 MW to 1340 MW continuous. These additions will also improve the resiliency of the grid backbone which Transpower has identified as a pre-requisite to enable renewable generation, electrify fossil fuel activities, and decarbonize the New Zealand economy.

5) When considering future HVDC Links, note that Voltage Source Converters (VSC's) produce a small fraction of the harmonics associated with the Line Commutated Converters (LCC's) presently used on the Benmore-Haywards HVDC Link. Consequently, there is less requirement for filtering and filter switching and associated maintenance. VSC's also require significantly less reactive support than LCC's to maintain rated transfer capacity.

Glossary

Block / Deblock	An HVDC converter deblocks its valve firing pulses to start and blocks the firing pulses to stop.
CAN	System Operator Customer Advice Notice issued 1 week to 36 hours ahead of real-time.
HVDC CE Risk	The HVDC Contingent Event Risk is typically the HVDC transfer (MW) that would be lost if one pole trips and after the healthy pole compensates as much as possible. The CE Risk might also be the HVDC transfer that would be lost if a harmonic filter trip reduces the HVDC transfer capacity.
GEN	System Operator Grid Emergency Notice issued after gate closure in the electricity market, within 1 hour of real-time.
Harmonic Filters	Harmonic filters connected to the AC buses at Haywards and Benmore help maintain power quality by absorbing harmonic currents from the HVDC converters and thereby reducing distortions on the AC voltage waveform. The filters also provide reactive power to offset the consumption of the HVDC converters.
HVDC GAC	Transpower National Grid Operating Centre HVDC Grid Asset Controller.
ODJB	Outdoor Junction Box. Control signals to each circuit breaker pass through a nearby ODJB.
POW Switching	Point-on-Wave Switching is used when closing filter bank circuit breakers to minimize the transient inrush current and thereby minimize the voltage disturbance and stress on equipment.
Power Limit	A defined limitation in HVDC transfer capacity (compared with a ‘Runback’).
Roundpower Mode	HVDC control mode which provides a smooth transition between Northward and Southward power transfer without a deadband around zero power transfer.

RPC	Reactive Power Control. At Haywards the RPC manages : • Switching AC filters • Switching shunt reactors • Setting voltage setpoints of synchronous condensers and the STATCOM • Tap changers on 220/110 kV interconnecting transformers
Runback	A defined reduction in HVDC power transfer by a fixed amount (compared with a 'Power Limit').
WRN	System Operator Warning Notice issued prior to gate closure in the electricity market, 1 hour before real-time.

1. Introduction

On Wednesday 5 October 2022, the System Operator provided an industry briefing on the tight generation situation to meet a forecast high demand associated with an unseasonable cold snap for the next 2 days, Thursday and Friday 6-7 October 2022. The industry responded by cancelling a number of planned generation and transmission outages so as to improve the resilience of the system for the 2 days of concern.

Transpower's scheduled live line work on HVDC Pole 2 that required restarts to be turned off was cancelled to improve resilience. Haywards HVDC Filters F3A and F3B were on a 2-week scheduled outage and were not recalled as the filter outage was expected to have no impact on the HVDC transfer rating.

At 04:28 on Friday morning, HVDC Harmonic Filter F4B tripped at Haywards Substation. There was no effect on the HVDC transfer and the filter was visually checked and the filter alarm reset at 05:36. Upon reset, the HVDC controls automatically reconnected F4B which immediately tripped again, leaving the HVDC in bipole operation and rapidly reducing power transfer by 270 MW. The power reduction resulted in an under-frequency event in the North Island which tripped North Island interruptible load.

Whilst the power reduction was being investigated, the HVDC controls automatically changed to Pole 3 monopole operation to maximize the HVDC transfer. However, the unplanned reduction in HVDC capacity, and increased contingent risk due to monopole operation, on top of the tight generation situation for the cold snap resulted in the System Operator declaring a Grid Emergency for the North Island over the Friday morning peak. Distributors in the North Island responded by shedding controllable load and the Grid Emergency ended after F4B was connected using manual control and the HVDC resumed normal bipole operation.

Transpower requested PBA Consulting to carry out an independent review of the HVDC power reduction event on 7 October 2022, primarily focusing on the HVDC operation. This review is based on Transpower's own investigations into the incident, technical documentation on the HVDC operation, and discussions with Transpower's HVDC & Power Electronics Group and the System Operator.

This report presents the findings of the independent review, which was carried out by Ranil de Silva, Technical Director of PBA Consulting (the Reviewer).

2. Discussions with Transpower Staff

During the course of this review, the reviewer held a number of discussions with the Transpower staff listed in Table 1.

Table 1. Discussions with Transpower Staff

Grid Delivery	HVDC & Power Electronics Engineering Manager
	Service Performance Manager-HVDC & Power Electronics
System Operator	Operations Manager
	Operations Planning Manager

3. Background to HVDC Operation

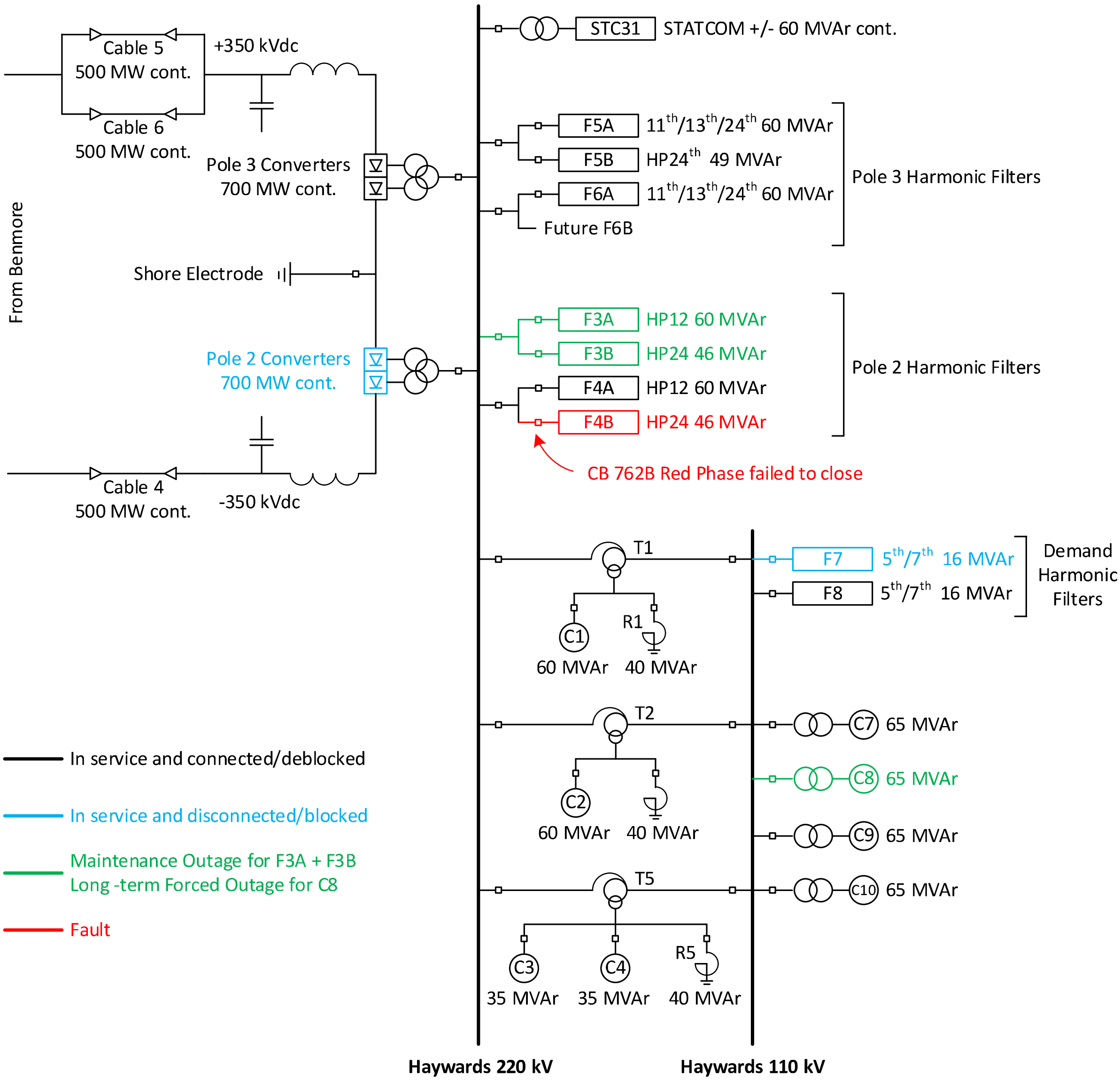
3.1. Haywards HVDC Converter Station

The Benmore – Haywards HVDC Link was initially commissioned in 1965 and underwent two major upgrades completed in 1992 and 2013.

Figure 1 shows a simplified single line diagram of the present Haywards HVDC converters for Pole 2 and Pole 3, and ancillary equipment including harmonic filters, synchronous condensers, and STATCOM. With all equipment in service, the HVDC Link is rated for 1200 MW Northward and 850 MW Southward.

The diagram shows the status of equipment just before Pole 2 deblocks and the HVDC controls attempt to connect Filter F4B, prior to F4B tripping and the HVDC power reduction.

Figure 1. Simplified Single Line Diagram for Haywards Substation at 0536 Before Pole 2 Deblocks and HVDC Controls Attempt to Connect Filter F4B



3.2. Roundpower Mode

The HVDC Link is normally operated in 'Roundpower Mode', as shown in Figure 2. Roundpower mode was implemented as part of the 2013 HVDC upgrade to permit a smooth transition between Northward and Southward power transfer without an approx ± 30 MW deadband around the zero transfer point.

The deadband results from the minimum current requirement of the HVDC converters preventing each pole from operating near zero power when deblocked. Roundpower mode circumvents the deadband by running Pole 2 and Pole 3 in opposite power transfer directions to allow net zero HVDC transfer.

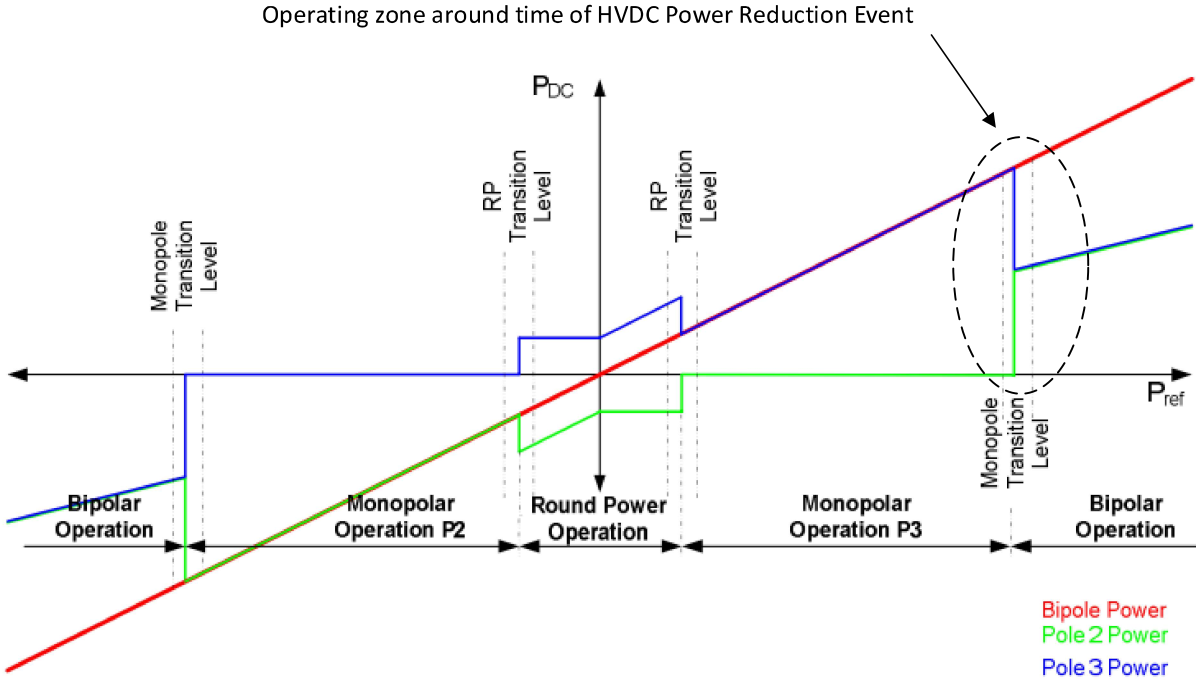
Roundpower mode is divided into 3 stages :

1) Roundpower operation close to zero net power transfer where Pole 2 and Pole 3 transfer power in opposite directions.
2) Monopolar operation where one pole is blocked and the other pole transfers power.
3) Bipolar operation where both poles transfer power in the same direction.

If there is a failure in the transition from bipole operation to monopole operation then Roundpower mode is disabled and bipole operation is maintained.

In respect of this report, Figure 2 also shows where the HVDC was being operated in Roundpower mode around the time of the power reduction event, changing back and forth between Pole 3 monopole operation and bipole operation.

Figure 2. Roundpower Mode [1]



[1] Adapted from Transpower/Siemens 'Station Control – System Information Manual', P3_E_B2_0321_XDC_F TP.OG.48.02, 3 September 2018.

3.3. HVDC Harmonic Filters

The Harmonic filters connected to the 220 kV buses at Haywards and Benmore help maintain power quality by absorbing harmonic currents from the HVDC converters and thereby reducing distortions on the AC voltage waveform.

The harmonic filters at Haywards are made up of sub-banks which are individually switched by a sub-bank circuit breaker as required to absorb harmonic currents and also to provide reactive power to support the system voltage. Each pair of sub-banks is connected to the 220 kV bus by a main bank circuit breaker. All of the switching duty is handled by the sub-bank breakers, with the main bank breaker used for protective tripping in the event of a filter sub-bank breaker failure. Of interest in this report is the sub-bank breaker CB 762B which switches Filter F4B.

The close command for each phase of the sub-bank breakers comes from a Point-on-Wave (POW) switching relay. POW Switching is used to minimize the transient inrush current into the filter bank and thereby minimize the voltage disturbance.

There are a variety of different types of filter banks connected to the 220 kV bus, filtering the characteristic harmonics from the converters :

- HP12 F3A, F4A filter 11th, 13th, and higher order harmonics
- TT 11/13/24 F5A and F6A filter 11th, 13th, 23rd, and 25th harmonics
- HP24 F3B, F4B, F5B filter 23rd, 25th, and higher order harmonics

There are 4 ‘A’ filters and 3 ‘B’ filters. A ‘B’ filter outage and loss of another ‘B’ filter will constrain HVDC power transfer. An allowance has been made in the design to install a 4th ‘B’ filter in the future.

There are also 2 harmonic filters connected to the 110 kV bus. These filter the 5th and 7th harmonics emanating from the local Wellington demand and do not affect HVDC transfer capacity.

The Bipole Operating Policy includes tables listing the HVDC power transfer capacity [2] dependent on :

a) Whether transfer is limited by harmonic voltage performance (power quality) or by the component ratings of the filters. Power transfer limits are only applied to avoid breaching filter rating limits (not harmonic performance limits).
b) Whether operation is monopolar or bipolar.
c) The connected filter banks.

In situations where demand is low and HVDC transfer is also low (typically over-night), it is desirable to connect only one 'A' and one 'B' filter in order to prevent the system voltage rising too high. The HVDC controls permit the operator to raise the power threshold for switching in additional filters if required to help control the system voltage.

The highest HVDC transfer capacity may sometimes be achieved in monopolar operation and sometimes in bipolar operation, depending on the connected filter banks. In respect of this report, the simultaneous outage of Filters F3A, F3B, and F4B results in a monopolar transfer capacity of 1001 MW which significantly exceeds the bipolar transfer capacity of 140 MW .

[2] Transpower 'HVDC : Bipole Operating Policy', Appendix G – Filter Configurations with Filter Outages, TP.OG.48.02, Issue 17, Oct 2021.

3.4. Pole Block for Multiple AC Filter Outages

The fact that HVDC monopolar transfer capacity can sometimes exceed bipolar transfer capacity led Transpower to add the 'Pole Block for Multiple AC Filter Outages Logic' to the HVDC control system in 2017. This was jointly developed by Transpower and Siemens to increase HVDC post-contingent capacity during filter outages by changing to monopole operation rather than staying in bipole operation after a filter tripping.

3.5. HVDC Representation in the Electricity Market Systems

The System Operator represents the HVDC transfer capacity in the electricity market systems by a model based on look-up tables derived from corresponding tables in the Bipole Operating Policy. This allows the model to calculate HVDC transfer limits based on equipment outages (including HVDC poles, filters, synchronous condensers, and transmission circuits) as well as transfer limits for contingent events.

The most onerous contingent event is typically a pole trip which may be partly compensated by increasing transfer on the healthy pole.

4. Description of HVDC Power Reduction Event

4.1. Timeline for HVDC Power Reduction Event

Table 2 shows a timeline for the HVDC Power Reduction Event of 7 October 2022, beginning with the first HVDC upgrade in 1992 and ending with Transpower's ongoing investigation into Filter F4B switching failures at Haywards substation. Figure 3 shows plots of the HVDC transfer over the whole event, and Figure 4 shows plots covering the few seconds around the HVDC power reduction.

Table 2. Timeline for HVDC Power Reduction Event 7 October 2022

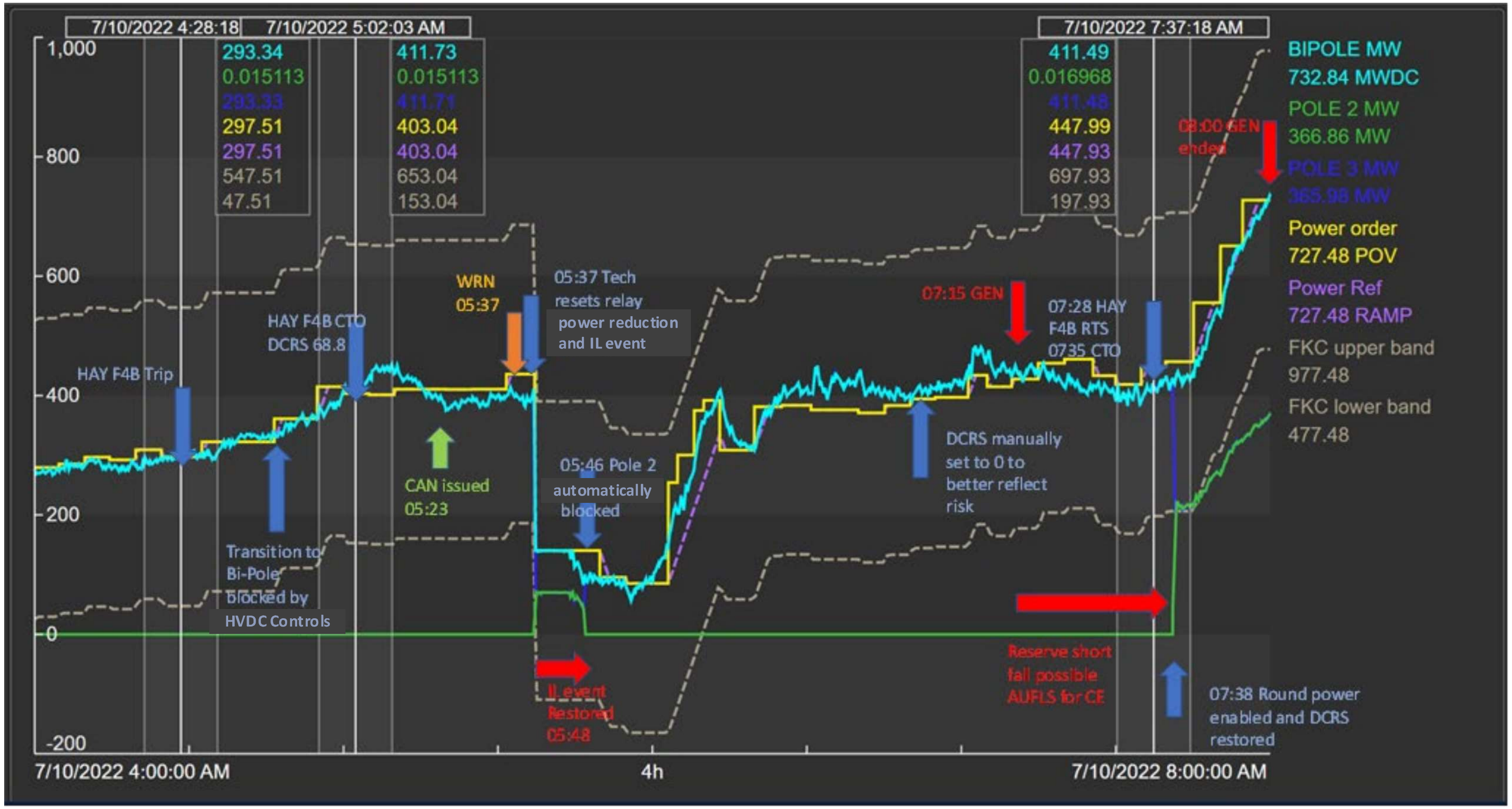
1992	Pole 2 220 kV harmonic filters and associated circuit breakers are installed as part of the first HVDC upgrade. The breaker Outdoor Junction Box (ODJB) equipment remains unchanged up to the event of 7 October 2022.
2004	Filter F4B circuit breaker CB 762B replaced
2013	Second HVDC upgrade.
28 November 2017	Implementation of 'Pole Block for Multiple AC Filter Outages Logic' in the HVDC control system to increase HVDC post-contingent capacity during filter outages by changing to monopole operation rather than staying in bipole operation after a filter tripping.
30 June 2018 2 November 2018 15 October 2021	Three events where Haywards Filter F3A circuit breaker CB 722A blue phase fails to close and trips. The cause for this intermittent fault was not pinpointed, even after extensive investigations by Transpower and external contractors.
3 October 2022	Start of 2 week scheduled maintenance outage on Haywards Filters F3A and F3B from 3 October – 14 October 2022, with an 8 hour recall time.
5 October 2022	System Operator industry briefing on the tight generation situation to meet demand for the forecast cold snap over the next 2 days, 6-7 October 2022.
14:59 6 October 22	The System Operator issues a CAN advising that there is a low residual forecast for the Friday morning, and requests increased energy and reserve offers for that period.
17:06 6 October 22	The System Operator issues a CAN advising that Transpower has cancelled live-line work on HVDC Pole 2, scheduled for Friday. The live-line work did not increase the HVDC contingent risk, but would have required disabling of automatic restart after a line fault. Cancelling the live-line work helped improve HVDC system resiliency.

Friday 7 October 2022	
04:00 – 04:28	HVDC transmitting about 260 - 300 MW North with Roundpower mode enabled. To help reduce the over-night AC voltage : • Pole 3 is run in monopole with the Monopole-Bipole Transition Level set to 350 MW. • Haywards Filters F4A and F5B are the only 220 kV filters connected and the threshold for connecting additional filters has been raised to delay connection of further filters.
04:28:25	The rising morning demand increases reactive consumption on the system, and there is no longer a need to minimize the number of connected filters. The HVDC GAC reduces the filter switching threshold to allow more filters to be connected.
04:28:28	The RPC connects Filter F5A.
04:28:32	The RPC attempts to connect Filter F4B, but CB 762B red phase fails to close and F4B trips. • The 'Pole Block for Multiple AC Filter Outages Logic' activates to hold the HVDC in monopole operation to maximize transfer capability. • As designed, the RPC does not automatically set Filter F4B to manual mode, and the filter remains available to the RPC, but cannot be switched until all protection alarms are cleared. • There is no effect on the HVDC transfer of 300 MW.
04:28:35	The RPC connects Filter F6A .
04:31	The HVDC GAC contacts the on-call Transpower HVDC engineer and requests the HVDC service provider to investigate the fault on-site. The HVDC GAC then resets all Filter F4B protection trip alarms except for the POW relay alarm which prevents the RPC from switching F4B. Filter F4B switching is left available to RPC for automatic switching.
04:32 – 05:35	The HVDC bipole transfer rises above the Monopole – Bipole Transition Level of 350 MW up to about 407 MW. The 'Pole Block for Multiple AC Filter Outages Logic' keeps Pole 3 in monopole operation and does not change to bipole operation because the combined outages of F3A, F3B, and F4B would otherwise limit HVDC transfer to 140 MW.
05:23	The System Operator issues a CAN advising there is an unplanned outage of Haywards Filter F4B. The effect of this outage is to increase the HVDC CE risk as the HVDC transfer will be limited to 70 MW as a monopole in the event that Filter F5B trips.

05:37	The System Operator issues a WRN advising there is a risk of insufficient generation and reserve offers to meet demand and provide N-1 security for a contingent event for the morning peak. This results from the limitation on HVDC transfer in the event that Filter F5B trips.
05:36:52	The HVDC service provider has arrived on-site and visually checked that Filter F4B and Circuit Breaker CB 762B are not damaged. The service provider then resets the POW relay alarm for CB 762B. As Filter F4B is still available to the RPC, resetting the POW relay alarm increases the bipole power limit to 1200 MW. The Roundpower Mode control now issues a 10 sec long deblock command to Pole 2 to transition to bipole operation whilst HVDC transfer is maintained at 410 MW.
05:36:54	2 sec after deblocking Pole 2 the RPC attempts to connect Filter F4B, however red phase fails to close a second time. The 'Pole Block for Multiple AC Filter Outages Logic' blocks Pole 2 and HVDC transfer is maintained at 410 MW by Pole 3 in monopole operation. Unbalance protection trips Filter F4B after 1.4 sec.
05:36:56	The HVDC controls unexpectedly deblock Pole 2 again due to the persistence of the 10 sec long deblock command.
05:36:59	The unexpected Pole 2 deblock signifies a failure of the Bipole to Monopole transition. This results in Roundpower mode being automatically disabled and continuation in bipole operation. With three Haywards AC filters now on outage (F3A, F3B for maintenance and F4B tripped) and the HVDC in bipole operation, an HVDC power limit was set by the control system which limited the total transfer capacity to 140MW. This causes a power reduction in HVDC transfer from around 410MW to 140MW within 2 seconds. The rapid HVDC power reduction results in the North Island frequency falling to 49.16 Hz and tripping North Island interruptible load before recovering.
05:46:52	The 'Pole Block for Multiple AC Filter Outages Logic' blocks Pole 2 again and Pole 3 maintains power transfer in monopole operation. This removes the 140 MW bipole limit and allows Pole 3 to operate in monopole up to rated continuous capacity of 840 MW.
05:57	The Transpower HVDC Engineer instructs the HVDC GAC to set Filter F4B in manual mode so it cannot be automatically connected.

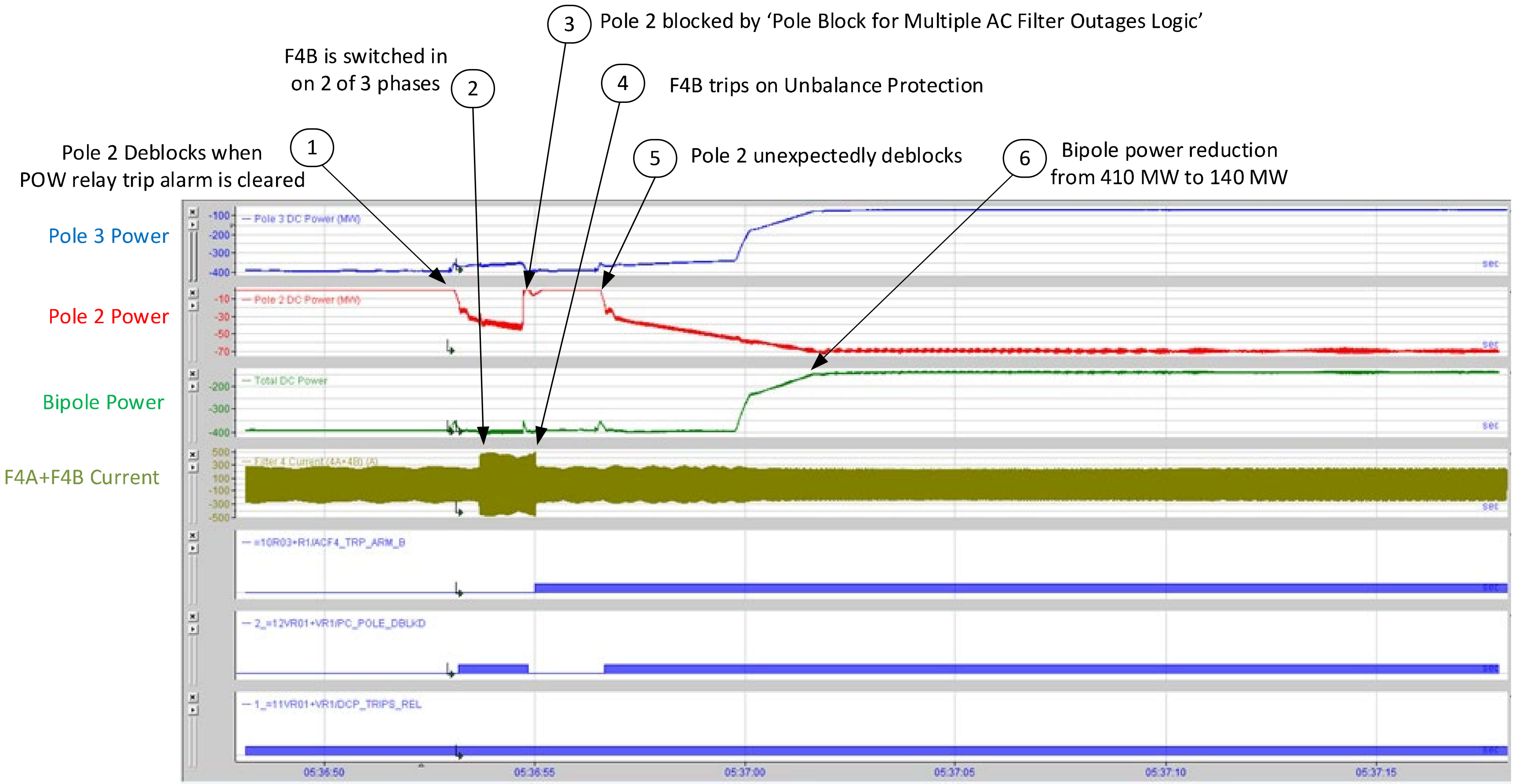
07:15	The restriction of the HVDC to Pole 3 monopole operation results in the System Operator issuing a GEN for the North Island advising there are insufficient generation and reserve offers to meet North Island demand and provide N-1 security for a contingent event. North Island distributors respond by shedding controllable load.
07:36	After on-site investigation, the HVDC engineers bypass the Filter F4B POW relay and request the HVDC GAC to attempt a manual close of CB762B. The manual close is successful and Filter F4B is left in service in Manual mode to prevent further automatic switching.
07:41	The HVDC GAC enables Roundpower mode and the HVDC changes from monopole to bipole operation at 411 MW transfer and power limit of 1200 MW.
08:00	The System Operator ends the Grid Emergency.
15-26 October 2022	Monitoring equipment is installed in the ODJB for Filter F4B CB762B to observe close signals while the breaker switching is tested. The 15th test showed the 125 V close signal through the ODJB being delayed, suggesting a high resistance contact in a switch or contactor which eventually broke over to let the signal pass through.

Figure 3. Overview of HVDC Power Transfer [3]



[3] Adapted from Transpower System Operator Diagram.

Figure 4. HVDC Power Transfer During Power Reduction [4]



[4] Traces adapted from HVDC Transient Fault Recorder.

4.2. HVDC Upgrades

The first HVDC upgrade completed in 1992 included the installation of the Pole 2 converters and associated harmonic filters and circuit breakers. Each circuit breaker installation included switches and relays housed in an Outdoor Junction Box (ODJB) to interface to the HVDC controls.

The second HVDC upgrade was completed in 2013 and included the installation of the Pole 3 converters, associated harmonic filters and circuit breakers. In respect of this report, the second HVDC upgrade did not include changes to the Pole 2 filter breaker ODJB components which remained unchanged up to the event of 7 October 2022 (however all Pole 2 filter breaker poles have been progressively replaced since 1992 at various times. CB 762B was replaced in 2004).

In 2017 the HVDC control software was upgraded by implementing 'Pole Block for Multiple AC Filter Outages Logic' to the HVDC control system. This was jointly developed by Transpower and Siemens to increase HVDC post-contingent capacity during filter outages by changing to monopole operation rather than staying in bipole operation after a filter tripping.

4.3. Intermittent Filter F3A Breaker Faults

From 2018 to 2021 there were 3 events where Haywards Filter F3A circuit breaker CB 722A blue phase failed to close and tripped. The cause for this intermittent fault was not pinpointed, even after extensive investigations by Transpower and external contractors. In respect of this report, the circumstances around these earlier trippings resemble the trippings of the Filter F4B breaker CB 762B red phase on 7 October 2022.

4.4. Filter and Synchronous Condenser Outages

On Monday 3 October 2022, Transpower began work on a 2-week scheduled maintenance outage on Haywards Filters F3A and F3B from 3 October – 14 October 2022. The outage management included an 8-hour recall time to return the filters to service in case they should be needed.

When scheduling HVDC maintenance outages, the System Operator's Operations Planning Team considers the effect of each outage on the HVDC transfer capacity, including the transfer capacity following a Contingent Event. The outages are coordinated to minimize the effect on the electricity market as far as possible. Filter outages are typically scheduled around October each year as the HVDC is not typically utilized at high capacity at this time.

The maintenance on Filters F3A and F3B did not affect the bipole transfer capacity of 1200 MW. The worst case effect of tripping an additional filter (F4B) would be to reduce the HVDC capacity to 1001 MW in monopole operation. Consequently, the HVDC contingent event risk remained unchanged as being the tripping of Pole 3.

In addition to the filter outages, Synchronous Condenser C8 has been on a long-term forced outage since August 2020. This is not material to this particular event, but is an example of how it is relatively common to have some HVDC reactive plant out of service.

4.5. Preparation for the Cold Snap

Weather forecasts began predicting an unseasonable cold snap for the country for Thursday 6 – Friday 7 October 2022. On Wednesday 5 October the System Operator held an industry briefing on the tight generation situation to meet expected high demand associated with the cold snap.

The industry responded by cancelling a number of planned generation and transmission outages so as to improve the resilience of the system for the 2 days of concern.

Transpower cancelled live-line work on HVDC Pole 2, scheduled for Friday. The live-line work did not increase the HVDC contingent risk, but would have required disabling of automatic restart after a line fault. Cancelling the live-line work helped improve HVDC system resiliency.

The System Operator did not request Transpower to recall Filters F3A and F3B from their scheduled outage as this outage was expected to have no impact on the HVDC transfer capacity.

4.6. Initial Trip of Filter F4B on 7 October

Around 04:00 in the morning of Friday 7 October, the demand was low and the HVDC was running at a relatively low transfer of 260 MW North. To help reduce the system over-night voltages, the HVDC was running in Roundpower mode with Pole 3 in monopole operation and the Monopole-Bipole Transition Level set to 350 MW. Haywards Filters F4A and F5B were the only 220 kV filters connected and the threshold for connecting additional filters was raised to delay connection of further filters.

The rising morning demand increased reactive consumption on the system, and there was no longer a need to minimize the number of connected filters to keep the system voltage down. At 04:28 the HVDC Grid Asset Controller (HVDC GAC) reduced the filter switching threshold to allow more filters to be connected.

The RPC immediately responded by connecting Filter F5A and then attempted to connect Filter F4B. The F4B sub-bank breaker CB 762B successfully closed blue and yellow phases but failed to close red phase. The imbalance in F4B phase currents then led the breaker to trip on unbalance protection.

The 'Pole Block for Multiple AC Filter Outages Logic' activated to hold the HVDC in monopole operation to maximize transfer capability. There was no change to power transfer because the combined outages of F3A, F3B, and F4B do not limit HVDC transfer when in monopole operation. In bipole operation with the same filter outages, the limit is 140 MW.

The HVDC control design does not consider the breaker 'Fail to Close' as being a 'Trip', consequently the RPC did not automatically set Filter F4B to manual mode, and the filter remained available to the RPC, but could not be switched because protection alarms had not been cleared.

As the RPC could not connect F4B, it connected Filter F6A as an alternative.

The HVDC GAC contacted the on-call Transpower HVDC engineer and requested the HVDC service provider to investigate the fault on-site. The HVDC GAC then reset all Filter F4B protection trip alarms except for the POW relay alarm (this can only be reset on-site) which prevented the RPC from switching F4B. Filter F4B switching was left available to RPC.

4.7. System Operator CAN and WRN

At 05:23 the System Operator issued a Customer Advice Notice (CAN) advising of an unplanned outage of Haywards Filter F4B. This outage increased the HVDC CE risk as the HVDC transfer would be limited to 70 MW as a monopole in the event that Filter F5B tripped.

The increased HVDC CE risk also resulted in the System Operator issuing a WRN advising a risk of insufficient generation and reserve offers to meet demand and provide N-1 security for a contingent event for the morning peak.

4.8. Second Trip of Filter F4B and HVDC Power Reduction

The HVDC service provider arrived on-site and visually checked that Filter F4B and Circuit Breaker CB 762B were not damaged. At 05:36:52 the service provider reset the POW relay alarm for CB 762B.

Figure 4 shows plots of the HVDC power on each pole over the 20 seconds following the reset of the POW alarm.

By this time the HVDC transfer had risen to 410 MW, which was above the 350 MW Roundpower mode Monopole-Bipole Transition Level. As Filter F4B was still available to the RPC, resetting the POW relay alarm increased the bipole power limit from 140 MW to 1200 MW. The Roundpower mode control began the transition from monopole operation to bipole operation by issuing a 10 second long deblock command to Pole 2 whilst maintaining net HVDC transfer at 410 MW (Point 1 on Figure 4).

2 seconds after deblocking Pole 2 the RPC attempted to connect Filter F4B (Point 2 on Figure 4), however red phase failed to close a second time, and the 'Pole Block for Multiple AC Filter Outages Logic' blocked Pole 2 (Point 3 on Figure 4) followed by unbalance protection tripping Filter F4B after 1.4 seconds (Point 4 on Figure 4). HVDC transfer was maintained at 410 MW by Pole 3 in monopole operation.

About 2 seconds after the return to Pole 3 monopole operation, the HVDC controls unexpectedly deblocked Pole 2 due to the persistence of the 10 second long deblock command from the initial Pole 2 deblock (Point 5 on Figure 4).

The unexpected Pole 2 deblock signified a failure of the Bipole to Monopole transition. This resulted in Roundpower mode being automatically disabled and the HVDC continuing in bipole operation.

With three HAY AC filters now on outage (F3A, F3B for maintenance and F4B tripped) and the HVDC in bipole operation, an HVDC power limit was set by the control system which limited the total transfer capacity to 140MW. This caused a 270 MW power reduction in HVDC transfer from around 410 MW to 140MW within 2 seconds (Point 6 on Figure 4).

The loss of HVDC transfer resulted in the North Island frequency falling to 49.16 Hz and tripping interruptible load before recovering.

About 10 minutes later, the 'Pole Block for Multiple AC Filter Outages Logic' blocked Pole 2 again and Pole 3 maintained power transfer in monopole operation. This removed the 140 MW bipole limit and allowed Pole 3 to operate in monopole up to rated continuous capacity of 840 MW. Even though this Pole 2 block helped increase HVDC transfer capacity to provide power to the North Island, it is not clear why the block was delayed for so long.

At 05:57, the Transpower HVDC Engineer instructed the HVDC GAC to set Filter F4B in manual mode so it could not be automatically connected by the RPC.

4.9. System Operator GEN

Pole 3 monopole operation maximized HVDC power transfer capacity, however a Pole 3 trip could not be immediately compensated by Pole 2. Consequently HVDC power transfer was limited by the availability of North Island reserves to compensate for a Pole 3 trip.

As the morning peak demand approached, the already tight generation situation together with the restriction of the HVDC to Pole 3 monopole operation resulted in the System Operator issuing a Grid Emergency Notice (GEN) at 07:15 for the North Island. This advised there was insufficient generation and reserve offers to meet North Island demand and provide N-1 security for a contingent event over the morning peak.

North Island distributors responded by shedding controllable load. This restored N-1 security and there was no requirement to disconnect customers.

4.10. Temporary Fix to Filter F4B and CB 762B

After an on-site investigation, the HVDC engineers theorized that the CB 762B POW relay had malfunctioned and failed to send a close signal to the red phase breaker.

The HVDC engineers bypassed the POW relay and requested the HVDC GAC to attempt a manual close of CB 762B. The manual close was successful and Filter F4B was left in service in manual mode to prevent further automatic switching.

At 07:41 the HVDC GAC enabled Roundpower mode and the HVDC changed from Pole 3 monopole operation to normal bipole operation at 411 MW transfer and a transfer capacity 1200 MW. The contingent event risk was significantly reduced by the ability of one pole to compensate for a trip on the other pole.

The return of the HVDC to normal operation allowed the System Operator to end the Grid Emergency at 08:00 .

The Reviewer's discussions with the System Operator Operations Manager indicated that leaving Filter F4B connected in manual mode would have minimal effect on reducing over-night voltages because at least one 'B' filter was typically always connected.

The Bipole Operating Policy also indicates that leaving Filter F4B connected in manual mode will not aggravate the Temporary Over-voltage (TOV) following a HVDC bipole trip because the AC Voltage Limitation Control will still trip filters that are in manual control.

4.11. Subsequent Investigations

Over the following 3 weeks, Transpower HVDC engineers continued to investigate the tripping of Filter F4B by CB 762B. Monitoring equipment was installed in the ODJB for CB762B to observe incoming close signals from the POW relay and outgoing close signals to each breaker phase.

The breaker operation was repeatedly tested by switching F4B and eventually the 15th test showed the 125 V close signal through the ODJB to the red phase breaker being delayed, suggesting a high resistance contact in a switch or contactor which eventually broke over to let the signal pass through. The POW relay itself did not appear to be malfunctioning.

At the time of writing this report, the investigation is continuing to more precisely pinpoint the fault location in the ODJB. Given that the ODJB components have not been changed since the first HVDC upgrade in 1992, there has been some discussion around replacing ODJB components on all Pole 2 filter breakers at both Haywards and Benmore.

5. Opportunities for Improvement

The analysis of the HVDC Power Reduction Event on 7 October 2022 suggests that there are a number of opportunities for Transpower to improve the reliability of the HVDC Link.

5.1. Replace Components in Pole 2 Filter Breaker ODJB's

The investigations by the Transpower HVDC & Power Electronics team into closing failures on Haywards Filter F4B CB 762B red phase, and previously Filter F3A CB 722A blue phase, suggest that there may be a high resistance contact in either a switch or contactor housed in the breaker ODJB's. This intermittently blocks or delays the close signal from the POW relay from reaching the breaker. The contactor typically operates every close-open cycle of the breaker and will have had many operations since installation.

The Pole 2 filter ODJB components have not been changed since their original installation during the first HVDC upgrade in 1992. The HVDC & Power Electronics Team is currently considering replacing the components in all Pole 2 filter ODJB's at both Haywards and Benmore.

The Reviewer supports this approach, noting that replacing breaker ODJB components will require re-testing the signal paths through the ODJB, but will not require software modifications to the HVDC controls.

5.2. Change Breaker Fail-to-Close to Trip-to-Manual Control

The automatic reconnection of Filter F4B highlighted that if a filter circuit breaker fails to close, the present HVDC controls are designed to leave the filter available for RPC control. Resetting protection alarms will result in the RPC immediately (and unexpectedly) connecting the filter if it is still required.

It may be preferable to modify the HVDC controls to respond to a filter fail-to-close by setting the filter to manual (not available to the RPC). The HVDC GAC would then make the decision to make the filter available to RPC at a convenient time.

Note that in respect of this event, a manual filter connection or HVDC GAC making the filter available to the RPC is expected to have had the same outcome resulting in the same HVDC power reduction.

5.3. Fix Bug in 'Pole Block for Multiple AC Filter Outages Logic'

The HVDC Power Reduction Event has highlighted a 'bug' in the software for the 'Pole Block for Multiple AC Filters Outages Logic' which was implemented in 2017, subsequent to the 2013 HVDC upgrade.

It appears that the 10 second signal used to deblock a pole is not well coordinated with the block signal from the 'Pole Block for Multiple AC Filters Outages Logic'. As demonstrated in this event, the persistent deblock signal can reverse the transition from bipole operation to monopole operation and consequently disable Roundpower mode, leaving the HVDC in bipole operation.

In this event, the bipole operation with filter outages resulted in a 270 MW reduction in HVDC transfer from around 410 MW to 140MW. If Pole 3 had been previously transferring 840 MW in monopole operation (perhaps to compensate for tripping a large generator), then the power reduction could potentially have been as high as 700 MW which could have triggered Automatic Under-frequency Load Shedding.

Investigations into this bug should also include identifying why the 'Pole Block for Multiple AC Filter Outages Logic' blocked Pole 2 about 10 minutes after the power reduction event.

Fixing this bug is likely to require a significant amount of time, effort, and re-testing on Transpower's HVDC Simulator.

5.4. Improve Resilience by Adding a 4th 'B' Filter

The 2013 HVDC upgrade allowed for a future 'B' filter (F6B) to be installed at Haywards. The HVDC control systems have already been factory tested for the additional filter, awaiting future installation and commissioning. The additional 'B' filter will provide additional redundancy to make the HVDC more resilient to outages of the 3 existing 'B' filters at Haywards .

Transpower is presently considering adding the fourth 'B' filter as well as a second STATCOM to improve HVDC resiliency and increase HVDC Northward capacity from 1200 MW to 1340 MW. This will also improve the resiliency of the grid backbone which Transpower has identified as a pre-requisite to enable renewable generation, electrify fossil fuel activities, and decarbonize the New Zealand economy.

5.5. Future VSC Converters will Require Less Filtering

The HVDC technology employed in the present New Zealand HVDC link is based on thyristor Line Commutated Converters (LCC's). These converters require a significant amount of filtering for harmonic currents, and the filters are frequently switched as the HVDC transfer varies. The high switching duty results in stresses on the switching equipment and high maintenance requirements.

Future HVDC links are likely to be based on Voltage Source Converter (VSC) technology which is now economically competitive with the older LCC technology. VSC converters produce a small fraction of the harmonics associated with Current Source Converters. Consequently, there is less requirement for filtering and filter switching. VSC's also require significantly less reactive support than LCC's to maintain rated transfer capacity.